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Enclaves provide new insights on the dynamics of magma mingling: A case study from Salina Island (Southern Tyrrhenian Sea, Italy)

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Abstract

Three lava flows (hereafter, flows A, B, and C) from Salina Island (Italy) consist of basaltic andesitic enclaves dispersed in a dacitic matrix. Enclaves represent 8–12 vol.% of the erupted magma. The number of enclaves and the surface covered by the enclaves at each outcrop do not vary significantly with the distance from the vent in the flows A and B. These feature reflect the dynamics of magma mingling within the reservoir and not the kinematics of the lava flow. In the flow C, these parameters vary irregularly. The statistical entropy $S(t)$ of the enclaves, which is a measure of their spatial distribution (dispersion), is estimated in outcrops located at different distance from the vent. The Kolmogorov–Sinai entropy rate k, which describes the variations of $S(t)$ with time, is also determined. In the lava flow A, $S(t)$ increases linearly with time t for $0<t<0.4$; k is 0.04. For $t>0.5$, $S(t)$ attains its maximum value and maintains constant with increasing t. In the lava flow B, $S(t)$ linearly increases with t, and k is 0.01. In the lava flow C, there is not correlation between $S(t)$ and t. The comparison between the results from the analysis of the Porri enclaves and those from numerical experiments on the variation of $S(t)$ in chaotic advective mixing systems and from previous experimental models on magma mixing, allow us to draw some conclusions on dynamics of the basaltic andesite–dacite mingling in the magma chamber. Fully chaotic magma mingling systems show three evolution stages. An initial stage, which is unknown because of the disruption of the initial configuration of the interacting magmas, a second stage characterized by a linear increase of the statistical entropy with time, and a third stage, in which the uniformity of the system is reached, and the entropy does not vary with increasing time. A system in which the uniformity is never attained, is characterized by irregular variations of $S(t)$ with time. In the flows A and B, the relations between $S(t)$ and t are consistent with those of a fully chaotic dynamics possibly associated to convection. The basaltic andesite was uniformly distributed in the dacitic host due to the occurrence of convective movements driven by the injection of the basaltic andesite within the dacitic chamber. The mingling system recorded by the lava flow A evolved with a higher rate with respect to that of the flow B. This suggests that chaotic advection (stirring and folding) is more efficient in the magmatic system A than in B. On the contrary, the mingling system C is characterized by a non-uniform distribution of the basaltic andesite within dacite. This reflects the occurrence of a dynamics in which stirring and folding processes do not operate efficiently and are unable to uniformly distribute the dispersed phase within the continuous one. The decrease of k from A to B, and the lack of a measurable k in C, along with the observation that A and B were emitted before C, indicate that the efficiency of advective movements within the Porri magma chamber declined with decreasing time. Mingled magmas characterized by a homogeneous spatial distribution of enclaves or an initially inhomogeneous distribution evolving towards a homogeneous one are indicative of efficient advection processes that may

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favor magma mixing. Mingled magmas characterized by an inhomogeneous distribution of enclaves suggest low dynamical interaction between the two end-members. Magma mixing is not allowed.

Keywords: volcanology; petrology; magma mingling; enclaves; lava flows; entropy

1. Introduction

Enclaves have been recognized in plutonic and volcanic rocks, and their occurrence indicates the physical interaction (mingling) between magmas of different composition [1–4]. Geochemical and structural studies on enclaves are abundant [4–8] and references therein], and allow us to reconstruct the processes responsible for the mingling of magmas, which include: injection of mafic magma into a silicic one, disruption of the stratification of a magma chamber during eruption, vesiculation of a mafic magma within a densely stratified reservoir, floating of a layer of mafic magma into a more evolved magma due to vesiculation, or to coupled vesiculation and crystallization, and disruption of a solid layer of mafic magma.

According to results from fluid-dynamical experiments on immiscible liquids [9,10], recent studies suggest that chaotic advection, i.e., efficient stirring/stretching and folding, plays an important role in the dynamics of magma mingling [11–13]. The main evidence of chaotic advection is the coexistence, within the same magmatic body and at different length scales (10^{-4}–1 m), of enclaves characterized by a fractal structure and by morphological features similar to those recognized in chaotic systems, i.e., vortexes, folds and stirring structures. However, natural dynamical systems are not necessarily chaotic. Also, they may be characterized by different degrees of chaos [14,15]. In statistical mechanics, the degree of chaos of a dynamical system can be estimated analyzing the time evolution of two key-parameters [16–22]: the statistical entropy S, which is a measure of the spatial distribution (dispersion) of a system, and the Kolmogorov–Sinai entropy rate k, which describes the dynamic instability of trajectories in the phase space.

In this study, we analyze the spatial distribution of the enclaves hosted in three lava flows from the Porri volcano (Salina Island, Southern Tyrrhenian Sea, Italy). We determine the statistical entropy of the enclaves within these lavas at different distances from the vent, and calculate k. The collected data are discussed in light of results from numerical experiments and allow us to (a) provide a description of the time and spatial evolution of enclaves within their host, (b) have a relative estimate of the degree of chaos of the magma mingling system, and (c) discriminate between different chaotic dynamics within the magma chamber.

The paper is organized as follows. In a first section we describe the geological and geometrical features of the selected lava flows and enclaves. In the second section we present the theory on the evolution of S and k in chaotic mixing systems using numerical experiments. In the third section, we illustrate the analytical method used to determine S and k in the Porri lavas using enclaves. In the last two section, we present and discuss the results, and summarize the most relevant conclusions.

2. Geological setting and general features of the selected lava flows with enclaves

Salina Island (Southern Tyrrhenian Sea, Italy) consists entirely of volcanic rocks related to the activity of five main volcanoes emplaced between 430 and 13 ka (Fig. 1a [23–25]). Porri volcano (865 m a.s.l.) is located in the western part of Salina, and consists of 83 to 43 ka old lava flows and scoria fall deposits [25]. The composition of the Porri products ranges from basaltic andesites to dacites [24].

Most of the Porri lavas are texturally heterogeneous. They are characterized by the occurrence of dark enclaves hosted in a lighter matrix (Fig. 1b). Here, we select three of these lava flows, which outcrop in the southern sector of the Porri volcano (lava flows A, B and C in Fig. 1a). These lavas were emitted from the Porri crater during the last phase of activity of the volcano, which date back to about 43 ka. On the basis of the field relationships, the lava flows A and B were emitted before the flow C. Geochronological data on the selected lavas flows are unavailable and the time interval between the three effusive episodes cannot be estimated. The structural and geochemical features of the Porri lavas, as well the physical properties of the two interacting magmas, were extensively described in previous studies [26–29] and only the main features are reported here.